

ASSESSMENT OF STABILITY OF A REVITALIZED STREAM T12 IN ORLICKÉ ZÁHOŘÍ

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Abstract

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The aim of presented project is to execute an analysis and evaluation of stream-bed conditions for streams after revitalisation measures. Revitalisation of stream T12 in Orlické Záhory has been comprehensive, included changes of stream line and longitudinal and transversal profile. The evaluation was so provided in two absolutely different stream-beds.

The evaluation was focused on stream-bed ground and slopes stability, which were established on the base of tangential stress, scouring and nonscouring velocity and of mean velocity in vertical calculation. Then the individual methods of calculation were compared and the results were faced with actual status of stream-bed and supposed development of stream-bed morphology.

revitalization, stream-bed, stability, flow

Water is a vital part of our landscape, where it appears in many forms and all states of matter. With respect to our topic, we were mostly interested in water in its liquid state, more specifically surface flowing water. Water in the form of streams and currents is the backbone of ecological stability in the landscape.

Nowadays, the state of streams and currents is rectified within landscape-forming and revitalization programs as well as the topical flood prevention measures. Stream modification, or rather revitalization – return to ‘natural conditions’ – is highly demanding and calls for cooperation of many experts from different fields.

When designing and implementing stream revitalization, we need to take into account that a stream develops continually and cannot be evaluated without its relations; it is always an inseparable part of the surroundings, to which it fits and with which it is connected by many natural links. Due to the fact that we live in a cultural landscape, a return to purely natural conditions is not possible; a stream does not perform an ecological function only, but also social, aesthetic, landscape-forming and recreation functions. Therefore, a stream revitalization design is always an

outcome of many compromises of all participating parties. The purpose of river system revitalization is to remove or change negative consequences of former unsuitable “regulations” of water currents in open landscape, to renew their ecological function, while retaining the other functions of the stream.

This study assesses a stream that was regulated in the past and then revitalized: we assessed the state of the bed and its stability and the potential changes that occurred due to the implemented revitalization.

MATERIAL AND METHODS

Appropriate institutions and organizations were addressed to gain both current and historical data for the study. As the selected stream is under the agricultural and water management administration, this organization was addressed as the first.

Terrain survey, measuring and collection of material

The terrain survey concentrated on the section of the stream where revitalization had been implemented. The stream was surveyed as well as all constructions going across the stream. We concentrated on the shape of cross profile, the

width of the bed, and the slope of the banks. The constructions included timber reefs and boulder chutes.

Samples of soil were taken in the bottom and banks of the bed.

Laboratory tests

Soil samples were analysed in the laboratory of the Department of Landscape Formation and Protection, Faculty of Forestry and Wood Technology, Brno. Granularity was analysed using sieves and densitometer method and granularity curves were created. Based on the analyses, the effective grain was established – a quantity characterizing the particular soil. Further, d_{50} – the mean grain was established, based on the granularity curves.

Stream bed model creation

HYDROCHECK application, version 5.0, was used to model the uneven flow within the stream bed. The stream path was inserted using function of path import from a text file of coordinates of 381 surveyed points. In total, 108 cross profiles were entered – the detailed surveying of the stream in 2007. Bed roughness was set to 0.05 in the places of boulder chutes (there are 20 of them in the selected section) and 0.033 in the remaining parts (material: unreinforced gravel). Stream banks are densely covered in vegetation – their roughness in the model was set to 0.055; roughness in the places of bridges: km 0.045–0.053 and km 0.508–0.516, which are made of concrete culverts, was set to 0.03.

The calculation of the surface level and vertical velocities was conducted using the application for $Q_5 = 4.7 \text{ m}^3/\text{s}$; $Q_1 = 1.36 \text{ m}^3/\text{s}$; $Q_{355} = 0.008 \text{ m}^3/\text{s}$ and $Q_a = 0.057 \text{ m}^3/\text{s}$.

The stream path before revitalization was entered in the application manually – based on project documentation, 23 cross profiles were entered. The stream bed was modelled by four points, due to its prismatic shape of a regular simple trapezoid with a constant bottom width (1 m) and bank slope (1:1.5). The roughness in the bed was set to 0.055 for vegetation-covered banks; 0.033 for unreinforced gravel bottom; and 0.035 for bottom reinforced by quarry stone.

Bed stability assessment

Stability assessment based on non-scouring and non-deposition velocities in the bed

To assess the bed stability using the calculation of non-scouring velocity, we used the following equations:

$$v_{e1} = 5.88 \times h^{\frac{1}{6}} \times d_{ef}^{\frac{1}{3}} \text{ (m/s)} \quad [1]$$

based on Šamov:

$$v_{e2} = 3.7 \times d_s^{\frac{1}{3}} \times h^{\frac{1}{3}} \text{ (m/s)} \quad [2]$$

The obtained non-scouring velocities were used to calculate non-deposition velocities by multiplying them by 0.7:

$$v_{n1} = 0.7 \times v_{e1} \text{ (m/s)} \quad [3]$$

$$v_{n2} = 0.7 \times v_{e2} \text{ (m/s)} \quad [4]$$

The calculation of v_{v1} is based on the depth in the bed and the size of effective grain, the v_{v2} velocity is based on the depth in the bed but the bed material characteristic is the mean grain.

If $v_n < v < v_v \dots$ the bed is stable

$v > v_v \dots$ the bed is unstable

$v \dots$ mean profile velocity.

Particular velocities were put in graph in Excel for comparison.

Stability assessment based on calculation of tangential stress

a) bottom assessment

The shear stress caused by water current which affects the bottom (τ_0) can be calculated by:

$$\tau_0 = \rho \times g \times R_d \times i, \text{ (Pa)} \quad [5]$$

where

$\rho \dots$ water density (m^3/s);

$g \dots$ gravitational acceleration (m^2/s)

$$R_d \dots R_d = 0.95 \times R \text{ (m)} \quad [6]$$

$R \dots$ hydraulic radius (m);

$i \dots$ water surface slope.

The values for hydraulic radius and water surface slope were taken from the Hydrocheck application, from models of currents in the bed.

Calculation of critical tangential stress for trapezoid bed:

$$\tau_c = 760.8 \times d_e \text{ (Pa)} \quad [7]$$

where

$d_e \dots$ effective grain.

If $\tau_c > \tau_0 \dots$ the bottom is stable

$\tau_c < \tau_0 \dots$ the bottom is unstable

b) banks in the bed assessment

The assessment of the resistance of banks in the bed is based on the calculation of tangential stress (similarly to bottom assessment).

Calculation of tangential stress caused by water on horizontal plane:

$$\tau_0 = \rho \times g \times h \times i. \text{ (Pa)} \quad [8]$$

Based on b/h ratio, we establish dimensionless coefficient ε , for derivation to tangential stress effective on the slope

$$\tau_{0s} = \varepsilon \times \tau_0. \text{ (Pa)} \quad [9]$$

Number of stability η for particles in the flat bottom

$$\eta = \frac{21\tau_{0s}}{(\rho_s - \rho) \times d_s \times g}. \quad [10]$$

Number of stability for particles on the slope

$$\eta_s = \eta \left[\frac{1 + \sin(\lambda + \beta)}{2} \right] \quad [11]$$

λ the angle between longitudinal current and the direction of velocity vector (0)

$$\text{tg}\beta = \frac{\cos\lambda}{\frac{2\sin\gamma}{\eta \times \text{tg}\phi} + \sin\lambda} \quad [12]$$

γ bank slope angle;

ϕ natural angle of soil sloping (according to ČSN 731001)
safety degree SF:

$$\text{SF} = \frac{\cos\gamma \times \text{tg}\phi}{\eta_s \times \text{tg}\phi + \sin\gamma \times \cos\beta}, \quad [13]$$

the condition for slope stability safety: if

$\text{SF} > 1$... the slope is stable

$\text{SF} = 1$... limit value

$\text{SF} < 1$... the slope is unstable. (Mareš, 1997)

Stability assessment based on vertical velocities in the bed

The third method selected for the bed stability assessment was the comparison of vertical velocities at particular places in the bed with chart values of allowed velocities for the specific granularity of the material of the bottom/banks and the mean depth in the bed with the selected discharge.

The values of vertical velocities were gained from the calculation of the streamflow in the bed performed in the Hydrocheck application for discharges Q_5 , Q_1 , Q_{355} (Q_a). The velocities on the bed slope, at the slope toe and the maximum velocity at the bottom were assessed and compared with the value of allowed (non-scouring) velocities (Krešl, Bartůňková, 1993).

Slope stability in the revitalization proposals we support the use of grass carpets (Šlezingr *et al.*, 2011).

Statistical processing of velocities in stream beds

The processed statistical file is a file of data of maximum vertical velocities at the bottom in stream profiles. This file was selected because these data significantly characterize the potential change in the streamflow and they form a sufficiently large homogeneous set suitable for statistical processing.

The data were compared by matched pairs t-test, which allowed us to verify the following hypothesis: two normal distributions with the same (though unknown) variance, where two random choices come from, have the same mean values (or the difference of these mean values equals a specific number).

In our case, the values of velocities before and after revitalization should not be the same (zero differences); it is demanded that the velocities dropped.

RESULTS

Terrain survey and measuring in Orlické Záhoří T12

The stream rises in the north-eastern slope of the Orlické Mts. and flows through forest stands with quite a high gradient. Then it flows into an area called Orlické Záhoří, which is characterized by undulating grassy slopes towards the Divoká Orlice River. Stream T12 is a right tributary of the Divoká Orlice at its 120.8th km.

Catchment area $S_p = 2.74 \text{ km}^2$;
stream length $L_t = 3.93 \text{ km}$; gradient $I = 7.7\%$.

Mean long-term discharge $Q_a = 57 \text{ l/s}$.

The stream path of T12 in Orlické Záhoří was surveyed in detail. Geodetic measuring was performed using THEOMAT WILD T 1000. Measuring was connected to JTSK and all constructions in the stream (bridges, timber reefs and boulder chutes) were surveyed – 390 in total. The main aim of surveying was to gain digital data for the assessment of the current situation, i.e. the longitudinal slope, the cross profile and the stream path. Surveying was entered as the underlying data for the stream bed in the HYDROCHECK application.

The purpose of the revitalization, implemented in 2004, was to provide a stabilized state, as close to nature as possible. The section from the stream crossing with Orlické Záhoří-Bartošovice road to estuary in Divoká Orlice was revitalized. The bottom grade line was increased to level 0.4–0.6m, which corresponds to a depth in natural sections of the stream. Right- and left-bank edges were demolished alternately and thus an alluvial plain with 8m width in the bottom and 10m width at the crest was formed. By inserting transverse stabilization

constructions natural pools were formed. Sediments deposit in the bed and vegetation grows in summer. There is a gradual branching of the stream. The bed is crossed by two bridges, the first one at km 0.6112–0.6192 and the other at km 0.7696–0.7766; they are both constructed from concrete culverts of rectangular profiles 200/100 cm, the facing is made of stonework.

Samples of sediments were taken from the bottom and the bed slope toe. They were taken at three places of the selected revitalized section, in the lower part of the stream: km 0.000–km 0.121.

Generally, we can say that sediments continue to be deposited in the bed, there are islands of vegetation. In the bed, there is no visible erosion of banks; there are deeper enlarged pools under boulder chutes. The constructions are in a good condition, timber reefs and boulder chutes do not show any signs of damage.

Results of granularity analysis

Granularity analyses were conducted in stream T12 in Orlické Záhoví: samples from the bottom and the slope toe, both from the revitalized section and the section above the revitalization were analysed.

Material in the bed is gravel, often with an admixture of finer fraction. The bottom most often consists of well-graded gravel; the slope toe consists of gravel with an admixture of finer fraction. Samples taken in the upper section (above the revitalized part) contain rougher particles; samples from the lower section have admixture of finer particles.

Based on granularity analyses and the gained percentages of individual fractions, the size of **effective grain** was established for the calculation of tangential stress of the bottom.

- Sample 1 bottom (lower part of the monitored section): $d_e = 35.42$; $d_e = 14.14$ mm for LB (left bank); $d_e = 27.28$ mm for RB (right bank).

- Sample 2 bottom (middle part of the monitored section, under a boulder chute): $d_e = 16.02$ mm; $d_e = 25.73$ mm for LB; $d_e = 12.89$ mm for RB.

- Sample 3 bottom (middle part of the monitored section, above a boulder chute): $d_e = 11.19$ mm; $d_e = 33.14$ mm for LB; $d_e = 14.03$ mm for RB.

Further, the value of the **mean grain** d_s (d_{50}) was established; the value is used in the calculation of tangential stress on the slope as well as the calculation of non-scouring velocity in the bed based on Šamov. The value of the mean grain was derived from granularity curves.

- Sample 1 bottom (lower part of the monitored section): $d_{50} = 24$ mm $d_{50} = 3.5$ mm for LB; $d_{50} = 8$ mm for RB.

- Sample 2 bottom (middle part of the monitored section, under a boulder chute): $d_{50} = 7$ mm; $d_{50} = 7$ mm for LB; $d_{50} = 8$ mm for RB.

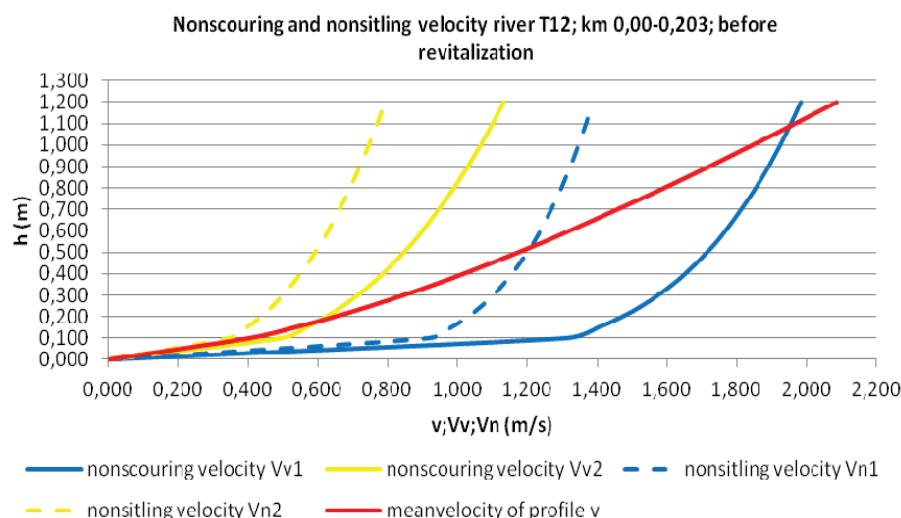
- Sample 3 bottom (middle part of the monitored section, above a boulder chute): $d_{50} = 3$ mm; $d_{50} = 12$ mm for LB; $d_{50} = 6$ mm for RB.

Results of stability assessment of the bottom and bed slopes

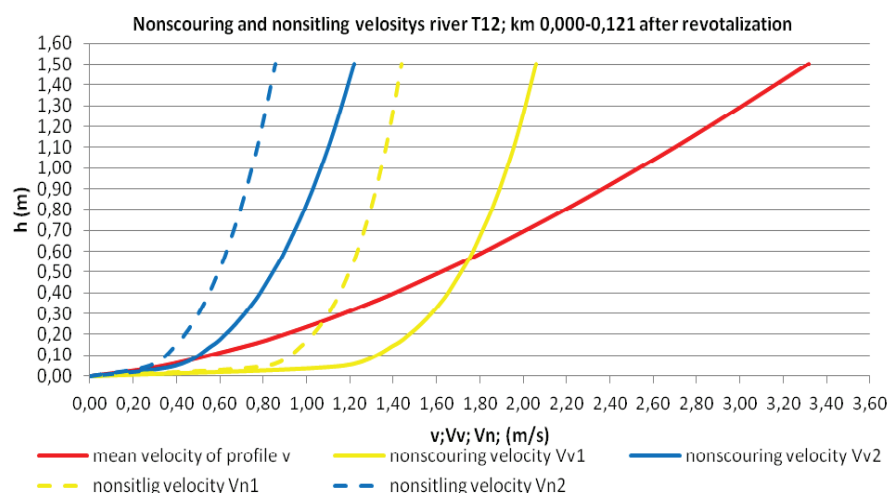
Calculation of non-scouring velocities

The calculation of non-scouring and non-deposition velocities in Excel is of an informative character only because the individual cross constructions, especially boulder chutes, are not taken into account. Roughness in the bed is entered as the mean, just as the slope of particular partial sections.

The following graphs for the 1st part of the monitored section show the dependence of non-scouring velocities V_{n1} , V_{n2} and non-deposition velocities V_{v1} and V_{v2} on the depth in the bed. The graphs and calculations were conducted for all parts of the monitored section, graphs for the 1st part are presented as an example (Fig. 1 and Fig. 2).



1: Orlické Záhoví-T12, non-scouring and non-sitling velocity km 0.00–0.203



2: Orlické Záhory–T12, non-scouring and non-sitling velocity km 0.000–0.121

Based on the calculations and graphs of non-scouring and non-deposition velocities, we can conclude that formulas for non-scouring velocities with characteristic d_c (non-scouring velocity V_{v1}) and d_s (non-scouring velocity based on Šamov V_{v2}) provide very different results.

Based on non-scouring velocity V_{v1} (d_c), the original bed is stable at a range of depths of 0.4 m–0.9 m, and the bed in the upper part is stable at a depth of 0.25–0.5 m. Based on non-scouring velocity V_{v2} , the bed is stable at much smaller discharges and depths of about 0.05–0.15 m. In the upper part (km 0.552–0.653), the bed is unstable even with the minimum depth of flow. The lower stability of the bed in the upper part is probably caused by a higher longitudinal slope when compared to lower parts.

Based on V_{v1} , the bed after revitalization is stable at depths of flowing water of 0.25–0.55 m in the lower monitored part (km 0.0–0.121). In the part km 0.121–0.665 the bed is stable at a depth of 0.1–0.2 m. Based on V_{v2} , the bed after revitalization is unstable in the entire monitored section.

The resulting tangential stress in the bed

Tangential stress for the bed of stream T12 was calculated for the bottom and the bank slope. The resulting values were organized in charts. The calculation was conducted for individual sections and for discharges Q_5 , Q_1 and Q_{355} to assess the bottom before revitalization; the state of the bottom after revitalization was assessed for discharges Q_5 , Q_1 and Q_a . The Hydrocheck application was unable to compute the discharge and depict surface for discharge Q_{355} in the bed after revitalization: discharge Q_{355} is too small. Bank stability was assessed for the capacity discharge, i.e. Q_5 or Q_1 .

With discharge Q_5 (4.7 m³/s), the loading imposed on the bottom decreased in the entire monitored section of the stream when compared with the state before revitalization. However, the bottom after revitalization does not meet stability conditions.

The stress caused by flowing water is higher than the critical stress of the bottom.

The section km 0.000–0.121 after revitalization is stable for discharge Q_1 (1.36 m³/s); in the remaining part the loading imposed on the bottom decreased considerably when compared with the state before revitalization: we can say that the bottom is nearly stable.

The bottom of T12 stream after revitalization is stable in the entire length for discharge Q_a (0.008 m³/s), the upper part (km 0.332–0.653) shows it was stable even before revitalization.

Banks of stream T12 are unstable in the entire length of the monitored section; their stability increased after bed revitalization.

Results of bed stability assessment based on vertical velocities in the bed

In total, 23 profiles were assessed for the original bed of T12; the material of the bottom based on grain mean (d_{50}) of 24 mm was used for the entire monitored section.

The mean grain in the slopes: LB – 3.5 mm; RB – 8 mm.

The velocity was at its limit for bottom resistance at discharge Q_5 (4.7 m³/s) flowing with a depth of about 1 m, $v = 0.18$ m/s; for left slope $v = 0.15$ m/s; for right slope $v = 0.16$ m/s.

When assessing discharge Q_1 (1.36 m³/s), depth of about 0.55 m, the velocity at the bottom was $v = 0.18$; left slope $v = 0.14$ m/s; right slope $v = 0.15$ m/s.

At discharge Q_{355} (0.008 m³/s), the limit non-scouring velocities for a depth of about 0.15 m were 0.15 m/s for the bottom; 0.12 m/s for the left slope; 0.13 m/s for the right slope.

The bed was assessed as unstable for the entire monitored section for discharge Q_5 and Q_1 ; at discharge Q_{355} slopes are stable in some places, the bottom and the slope toe are unstable.

Within the vertical velocity assessment in the revitalized bed, 39 profiles of the total 108 profiles

were assessed – the selected profiles were located each 30 m.

The velocity calculations show that with discharge Q_5 and Q_1 the bed is unstable, with discharge Q_a some profiles are stable both at the bottom and in the slopes.

However, taking into account that the slope is covered in grass, the allowed velocity will increase to 1.2 m/s at discharge Q_5 , and 0.9 m/s at discharge Q_1 , the slopes of the stream are stable.

Results of statistical assessment of the velocities

The maximum vertical velocities in stream T12 were assessed at 23 profiles. They were profiles in the original bed and for the set of velocities after revitalization they were matched with profiles in the corresponding logging of the new bed.

The statistical test proved a change in the maximum velocities in the bed of stream T12 before and after revitalization. The zero hypothesis is not met, which means that $T > T_{krit}$, i.e. the assessed velocities are not the same.

Summary of results

The aim of the study was to assess the state and stability of stream T12 in Orlické Záhoví, before and after revitalization. The conducted revitalization was complex, i.e. modifying both cross and longitudinal profile.

After characteristics of the stream bed and material of the bottom and slopes were determined, the assessment of stream bed stability was performed based on calculations. Three approaches were selected to assess the stability of the beds of the selected stream.

The results of individual methods for stability assessment in stream T12 after revitalization are presented in Table I. The method for stability calculation based on non-scouring/non-deposition velocities (V_{v1}/V_{n1}) provides similar results to the assessment of tangential stress on the bed bottom. The method of vertical velocity assessment sees the bed (with some exceptions) as unstable; the method based on non-scouring/non-deposition velocities (V_{v2}/V_{n2}) gives very similar results.

Considering the results of the terrain survey we can conclude that the revitalization started natural bed-forming processes thanks to the creation of a new shallow bed with inserted boulder chutes.

Sediment deposition is in process at the bottom of the bed (stability assessment based on V_{v2}/V_{n2} corresponds with this), below boulder chutes there are deep wide pools being formed.

Each of the selected methods for stability assessment has its drawbacks. As has been proved in the case of non-scouring velocity calculations, the selection of the formula from the wide range literature provides is highly important. The method of tangential stress calculation can distort the results, especially concerning slope stability as it does not take into account possible reinforcement by vegetation – the calculation uses the slope angle and granularity of the material in the slope. However, the used methods are sufficiently plausible for our conclusions.

DISCUSSION

Stream T12 in Orlické Záhoví is a stream that has been revitalized relatively recently. The revitalization was of a complex character, both cross and longitudinal profiles were changed, as well as the direction conditions. The stream in the monitored section flows through a meadow; there are no conditions limiting a natural development of the stream. The bed is broad and shallow; slopes are gentle and covered in grass. Based on the terrain survey, we can conclude that no significant erosion is visible in the bed, with exception of pools under boulder chutes. Sediments deposit in the bed – islands are being formed and covered in vegetation. Changes in the stream path are gradual and only slight, the bed is still kept within the axis formed during revitalization. However, this can be explained by the fact that no extreme discharge has occurred in the bed since the revitalization. The calculations of stability show that in the case of this revitalization the bed is unstable: probably, the aim was not to design a stable bed but to provide conditions for further, as natural as possible, development of the stream, both in the cross profile and direction conditions. That is why the bed is broad and shallow with gentle slopes. In case of greater discharge of floods, slope destruction will probably will occur in outside bends and sedimentation of a larger amount of material will occur in other places. However, this is highly demanding in this stream – the stream has the space to form its own bed in the shallow alluvial plain.

I: Summary results of the assessment by individual chanel stability methods – river T12 after revitalization

section	stability								
	1. $V_{v1}, V_{n1}/V_{v2}, V_{n2}$						2. τ (bed)		3. vertical velocities (bed)
	Q_5		Q_1		Q_a		Q_5	Q_1	Q_a
km 0,00–0,121	no	no	yes	no	no	yes	no	yes	yes
km 0,121–0,508	no	no	yes	no	no	no	no	no	yes
km 0,508–0,665	no	no	no	no	no	no	no	no	yes



erosion



silting

Nowadays, a possible implementation of a complex revitalization of a stream depends heavily on ownership relations of the lands along the stream. If the available space along the stream is not

sufficiently broad, we can only work with the current bed and thus the range of possible revitalization measures is very limited.

SUMMARY

In this project, an evaluation of stream after revitalization measures – stream T12 in Orlické záhoří was done. It was determined status of stream before revitalization on the base of obtained project documents. Actual status of stream-beds was evaluated by way of particular terrain reconnaissance. Stream-bed and all structures at chosen part of the stream T12 was geodetically located in detail and soil samples from stream-bed ground and slopes were taken.

When it was obtained sufficiency of information about stream-bed status before and after revitalization, geometric and hydraulic characteristics of stream-bed was calculated. Taken soil samples were classified on the base of grain size and Czech standard CSN 731001.

Evaluation of stream-bed stability came next determination of stream-bed profiles and stream-bed ground material characteristics. Evaluation was based on calculations, nonscouring velocities, calculation of tangential stress and evaluation of velocities at concrete position of transversal profile and their comparison with tabular permissible velocity for stream-bed material.

For detailed summary about flows in chosen stream a computer program HYDROCHECK was used. By this program the location of stream before and after revitalization was inserted and discharges Q_5 , Q_1 , Q_{355} (Q_a) were graphically created. So there were created water levels of these discharges, determined depths for each discharge and next, level slopes were used for stability calculation. In Hydrocheck the mean velocities in vertical for individual profiles too were calculated. They were considered next in the frame of stream-bed stability evaluation.

Resulting calculations of stability show, that several methods can give different results. It is evident especially by calculation of nonscouring velocities, where the selection of formula mostly affects the result. Material in stream-bed can't warrant profile stability for discharges Q_5 or Q_1 . But if there is a grass sod at slopes, stream bed will resist the water flow in these discharges. Stream T12, where revitalization was comprehensive, improvement of stability is significant. Results of tangential stress calculation are close to stabile status.

Revitalization of stream T12 certainly achieves an improvement of stream-bed. It caused improvement of stream-bed status appearance, revival and stability. There are alternated sections with quick flowing water (at stabilized chutes) and sections with slow flows in the stream bed.

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